CR-TMS: Connected Vehicles enabled Road Traffic Congestion Mitigation System using Virtual Road Capacity Inflation

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Abstract— **Road traffic management experts are constantly striving to develop, implement and test a number of novel strategies to reduce traffic congestion impact on the economy, society and the environment. Despite their efforts, these strategies are still inefficient and a call for advanced multidisciplinary approaches is needed. We, therefore, introduce in this paper an original traffic congestion mitigation strategy inspired from a well-known technology in wireless communications, i.e. cognitive radio technology. Our strategy exploits Connected Vehicles technology along with the often under-utilized reserved lanes, such as bus and carpool lanes, to virtually inflate the road network capacity to ease traffic congestion situations. Two variants of our strategy have been evaluated using simulation and the obtained results are very promising in terms of the achieved reduction in average travel time for different vehicle classes including buses as well.**

Keywords – **Connected vehicles, Smart cities, Road traffic congestion, Intelligent transportation system .**

I. INTRODUCTION

The race towards building the first smart city with all the revolutionary features and services offered to its inhabitants is at its highest peak, especially in developed countries that have the financial resources and advanced technologies needed to achieve this goal. Indeed, smart cities are attractive because they advocate a futuristic vision of cities building sustainable ecosystems while promoting citizen welfare and economic growth. A smart city fosters the use of advanced ICT-driven solutions to smartly and efficiently monitor and manage its critical assets such as energy, water, and transportation infrastructure. Such an ambition can become a reality only with joint efforts from governmental, industrial, academic and social actors. Building smart cities, however, strongly depends on various enabling advanced technologies (e.g. intelligent sensing, 5G/B5G networks, Artificial Intelligence and connected vehicles, etc.) to support sustainable developments such as smart buildings, energy and smart mobility. Intelligent Transportation Systems (ITS) are considered as a main pillar of smart cities since the efficiency of several major services is reliant on their robustness and security level [1]. Transport experts foresee that ITS will be mainly comprised of automated or autonomous vehicles, cutting-edge transportation infrastructure in addition to innovative applications and services. Such infrastructure includes intelligent traffic light controllers, advanced traffic monitoring equipment and sensing devices, etc. The main mission of ITS is to efficiently control and mitigate road traffic congestion problem that most cities suffer from.

The excessive traffic congestion in urban areas is mainly due to the increase in the vehicles' fleet, which in return causes accidents and worsens the congestion level on the already deteriorated road infrastructure. Traffic congestion has major impacts on the environment, the economy, and the population health, as stated in [2]. The last decade has witnessed an unprecedented revolution in developing advanced ICT driven solutions to mitigate the increasing road traffic congestion and alleviate its resulting impact on travelers' journey experience, road safety, air quality and economy. Such solutions include advanced vehicle routing and re-routing systems, such as [3] and [4], traffic light signals optimization techniques [5], smarter and more efficient parking management systems [6], bio-inspired computational intelligence [7] and machine learning [8] assisted transportation systems, etc. To complement these efforts, we propose an original traffic congestion mitigation system named CR-TMS (Cognitive Radio based Traffic Management System) that implements two traffic mitigation solutions: CRITIC (Cognitive Radio Inspired TraffIc Congestion) for which the preliminary evaluation results have been published in [9] and its extension CRITIC+. Compared to CRITIC, CRITIC+ takes into account the accumulated delay during the vehicle journey to compute a fair probability of access to the under-utilized priority lanes. It also defines different classes of vehicles each has its own priority for promotion to the VIP class that grants access to priority lanes, and thus accelerates the vehicle progress towards its destination. Moreover, more accurate and fine grained evaluation is performed using more realistic parameters to accurately measure the impact of both CRITIC and CRITIC+ on the achieved average travel time.

The remainder of this paper is organized as follows. In Section II, we give a global view of the TMS architecture and its main components. Section III presents the main idea of CRITIC+ and describes the different classes of vehicles considered in this work. The simulation setting and experiments evaluation results are discussed in Section IV, followed by concluding remarks in Section V.

II. TRAFFIC MANAGEMENT SYSTEM: AN OVERVIEW

In the context of Smart Cities, the Traffic Management System (TMS) has a major role of smoothing traffic flow in order to avoid congestion. This latter has direct consequences on drivers, in terms of the experienced stress and increased

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travel delay, and leads to increased noise, energy consumption, and environmental pollution, which considerably degrades the quality of life of the city inhabitants.

The regulation of traffic flow necessarily passes by taking into account the environment and therefore the number of vehicles on the road, their directions, the topology of the road and the events impacting it such as the presence of roadworks, pedestrians and the occurrence of unpredictable incidents. This environment is typically monitored by deploying cameras or radars and different types of IoT sensors, in addition to Intelligent Traffic Lights (ITLs) equipped with communication capabilities that enable them to communicate with connected vehicles and thus, on the one hand, collect useful traffic data, and on the other hand notify them of any adjustments to road lanes usage rules or driving policies that require coordinated actions from them. These different probes regularly report traffic data back to the data collection and aggregation modules. Based on the data collected and processed, the Intelligent Traffic Light Controllers (ITLCs) can make the proper decisions to smooth traffic flow locally by sending recommended adjustments to the ITLs that they control. However, local traffic regulation, although useful, can sometimes create congestion at other levels, as reported in several studies [1]. In fact, the limited view of the overall traffic situation means that these local decisions can be wrong globally and lead to complex congestion situations that cannot be controlled easily.

Accordingly, we introduce, in the architecture shown in Figure 1, a global congestion evaluation engine that ensures that adjustments are made based on the acquisition of the overall view of traffic situations across the road network in a section of an urban area. Based on its global view of the traffic situation, this engine enables the optimization of local decisions made by ITLCs. The idea here is not to decide everything at the global congestion evaluation engine level, which would make the system very difficult to scale-up, but to allow ITLCs to adjust their decisions to make them better overall.

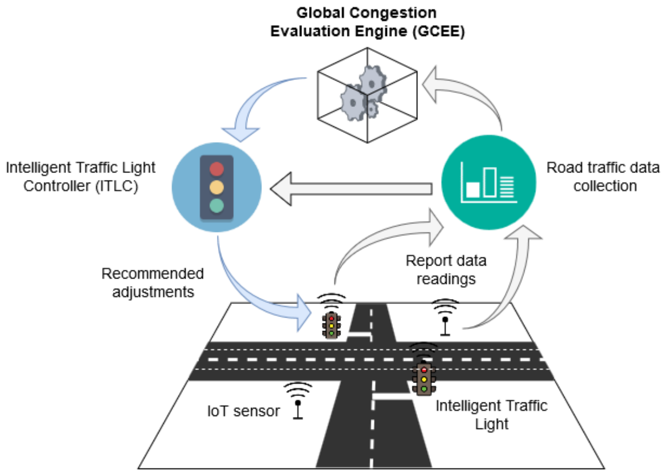


Fig. 1: Traffic management system: from traffic data collection to congestion mitigation

III. Cognitive Radio-based Traffic Management System

In an attempt to virtually increase the road network capacity without building new roads that require substantial financial investment we propose to extend the existing TMSs by adding a new feature that enables opportunistic access to reserved lanes for a selected set of connected vehicles. The extended TMS is named CR-TMS (Cognitive Radio-based TMS) inspired from the cognitive radio technology principle widely adopted in wireless devices to increase their share of bandwidth, so that their transmission throughput improves, under certain constraints when their primary spectrum is overloaded. Similarly, CR-TMS is primarily intended, on the one hand, to relieve the congestion on regular (i.e., non-priority) road lanes, allowing vehicles to move at higher speed and thus increasing the traffic throughput; and on the other hand, optimizing the usage of reserved (i.e., priority) lanes capacity under certain conditions without slowing down their primary users (e.g., buses, carpooling vehicles, etc).

CR-TMS has similar architecture to the TMS shown in Figure 1 where the existing ICT-based road infrastructure is used for traffic data collection and ITLCs are leveraged to assess the traffic conditions on non-priority and priority lanes that they control. ITLCs are also responsible for creating access opportunities, for non-prioritized vehicles, to priority lanes if the access conditions are met. Such access conditions are evaluated either locally, by the ITLC, or at the global level by the GCEE, as shown in Figure 1. As a result of this evaluation CR-TMS decides about the optimal actions to be taken through triggering CRITIC or CRITIC+. In CR-TMS, we assume that the penetration rate of connected vehicles on the road is 100%, so the impact of human-driven cars is neglected in this work. CR-TMS intervention to reduce congestion is subject to the following conditions:

- Traffic using non-priority lanes is moving at a slow speed due to recurrent congestion or as a result of an unpredictable event. The speed reduction, compared to the speed limit of the lane, that makes this condition valid is expressed as follows.

$$\frac{FF_{speed} - C_{speed}}{FF_{speed}} \geq threshold_1 \quad (1)$$

  where FF_{speed} refers to the free flow speed and C_{speed} denotes the current measured speed on this road lane. $threshold_1$ is a value dynamically set to reflect how fast CR-TMS should react to traffic congestion occurrence to anticipate any further consequences.
- A priority lane is currently under-utilized because the number of priority vehicles using it is below the recommended usage rate by the traffic authority to ensure efficient usage of the road infrastructure. The usage rate that makes this condition valid is expressed as follows.

$$\frac{|RU_{rate} - CU_{rate}|}{RU_{rate}} \geq threshold_2 \quad (2)$$

Such that CU_{rate} defines the current usage rate observed on the priority lane while RU_{rate} represents the recommended usage rate of such lane by the priority vehicles.

Once the above conditions are met, CR-TMS will trigger CRITIC+ whose main operations are summarized in the Algorithm 1. Please note that CRITIC+ defines three classes of vehicles as explained below.

- Prioritized vehicles (P-vehicle): such as buses and carpool vehicles, any vehicle in this class will, by default, use any Priority Lane (PL) in its route to the destination.
- Non-Prioritized Vehicles (NP-vehicle): any regular vehicle that does not belong to the above class. By default, any vehicle in this class will use the Non-Priority Lanes (NPL) during its route to the destination.
- VIP-vehicle: this class is defined dynamically where a number of vehicles belonging to NP-vehicle class are selected to temporarily use the available priority lanes.

Algorithm 1: The main operations of CRITIC+

```
Result: The set of VIP-vehicles
Input: Road network edges;
IoT sensors reading;
ITL collected data;
for Each road segment do
    if PL exists then
        if At least one P-vehicle is using PL then
            Revoke PL access to VIP-vehicle class;
            Reinitialize VIP-vehicle class;
        else
            - Determine the hosting capacity of PL;
            - Determine the required load reduction in
              congested NPLs;
            - Determine the size of the subset of
              vehicles to be promoted from NP-vehicle
              class to VIP-vehicle class;
            - Compute the selection probability of each
              NP-vehicle currently using NPLs;
            - Select the vehicles to be promoted and
              update VIP-vehicle class;
            - Notify the promoted vehicles;
        end
    else
        Check the next road segment;
    end
end
```

A. The promotion process: from NP-vehicle to VIP-vehicle

Once the conditions for the promotion are met, as shown in the above algorithm and Equations 1 and 2, CRITIC+ measures the hosting capacity of the priority lane (see Equation 3) and the required reduction of the load on the Non-Priority Lanes (see Equation 4) to determine the number of vehicles to be promoted (see Equation 5).

$$PL_{Hosting\text{-}capacity} = \frac{Length(PL) + Safety\ \ Distance}{AVG_{VL} +\ Safety\ \ Distance} \tag{3}$$

$$NPL_{Load\text{-}reduction} = \left(\frac{FFS_{NPL} - AVG_{Speed}(NPL)}{FFS_{NPL}}\right) \times \#Vehicles \tag{4}$$

$$Subset_{size} = \min(PL_{Hosting\text{-}capacity},\ \ NPL_{Load\text{-}reduction}) \tag{5}$$

Where $Length(PL)$ refers to the length of the priority lane, AVG_{VL} is the average length of a vehicle, FFS_{NPL} represents the Free Flow Speed of the congested non-priority lane while $AVG_{Speed}(NPL)$ denotes its current average speed. It is worth to mention as well that the Safety Distance is computed based on the maximum speed allowed in the priority lane.

The selection of vehicles to be promoted to the VIP-vehicle class is made based on three criteria:

- Their power source (i.e. electricity, hybrid, and fossil fuel), where an electric vehicle has a higher chance of promotion as it contributes more to transport sustainability. Moreover, the aim of this work is to support the emergence of electric vehicles use due to its positive impact on the environment.
- The remaining travel distance to reach the destination. Here, vehicles with longer trips have higher chances of being selected for promotion.
- The accumulated waiting time, at intersections and due to traffic congestion, since the start of the vehicle trip. Vehicles with longer waiting times are favorite for promotion.

For each non-prioritized vehicle i, normalized values of the above three criteria along with their corresponding weight values are used to compute its probability, as shown in Equation 6, for promotion to the VIP-vehicle class.

$$\Pr(i) = (W_{power} \times Power_{value}(i)) + (W_{trip} \times Trip_{value}(i)) + (W_{waiting\text{-}time} \times Waiting\text{-}time_{value}(i)) \tag{6}$$

Such that $Power_{value}$ is set to different values, in $]0,1]$, for electric, hybrid and fossil fuel vehicles. $Trip_{value}(i)$ is a normalized value representing the remaining travel distance for the vehicle i trip and calculated according to Equation 7. $Waiting\text{-}time_{value}(i)$ is a normalized value that denotes the accumulated waiting time of the vehicle i and is computed according to Equation 8.

$$Trip_{value}(i) = \frac{Trip(i)}{Maximum_{trip}} \tag{7}$$

Where $Trip(i)$ denotes the remaining distance to the destination for the vehicle i, while $Maximum_{trip}$ represents the maximum value of this distance among all the vehicles using this congested non-priority lane.

$$Waiting\text{-}time_{value}(i) = \frac{Waiting\text{-}time(i)}{Maximum_{waiting\text{-}time}} \tag{8}$$

Such that *Waiting-time*(i) represents the accumulated waiting time of the vehicle i during its trip so far while $Maximum_{waiting\text{-}time}$ refers to the maximum experienced accumulated delay among all the vehicles using this congested non-priority lane.

Now, the ITLC selects the non-priority vehicles with the highest $\Pr(i)$ values (i.e. the top $Subset_{size}$ vehicles) and notify them that they have been promoted to the class VIP-vehicle and are now able to move to the under-utilized priority lane(s). Notice that for safety and traffic efficiency purposes, the ITLC may choose to notify a lower number of vehicles than the selected $Subset_{size}$ vehicles, mainly based on their current positions within each lane.

IV. Performance evaluation and analysis

To evaluate the performance of CRITIC and CRITIC+, we conducted experiments using the microscopic traffic simulator SUMO and TraCI packages. We used 7×7 Grid network topology consisting of 2×2 lanes and set the distance between every two consecutive junctions to 250 m, similar to Manhattan road network in New York City. Two scenarios were tested, in the first one, the most outer lane on 25% of the network edges was used as a priority lane (i.e., a lane reserved for buses) while in the second scenario 50% of the edges have such a reserved lane. As an example, if we examine an area of $2km^2$ around the Grand Central Terminal in Manhattan we can find that 23% of edges have a reserved bus lane. The experiments were run 30 times with a varying seed value at each run. Three categories of vehicles are considered in the simulation: buses, private vehicles, and electric vehicles. The details of the simulation setting are summarized in Table I. The weight values for the three selection criteria, used in equation 6, are set to 1/3 each in our simulation but different values could be also used if traffic authorities want to give more importance to one specific criterion for example. During the simulation, non-prioritized vehicles with promotion probability greater than or equal to 0.6 are promoted to the VIP-vehicle class until the $Subset_{size}$ is reached or there is no further non-prioritized vehicle that meets the promotion conditions.

Parameter	Value
Map	Grid network: 7×7
Edge length	250m
% of bus lanes	25% and 50% of total number of lanes
Nb of vehicles	2200
% of buses	4%, 8% and 12%
% of Electric Vehicles (EV)	10%
Nb of simulation runs	30

TABLE I: Simulation setting

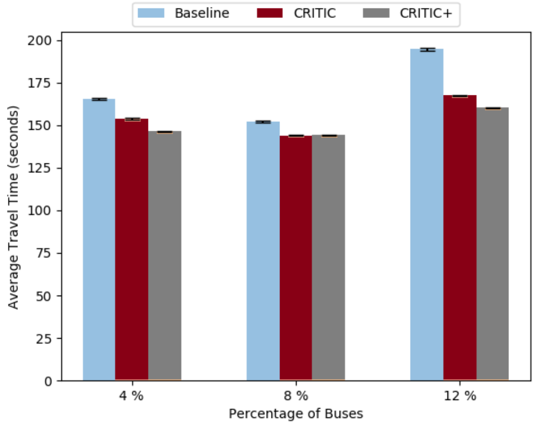
The results plotted in Figures 2 and 3 are measured for three use cases. In the baseline scenario, non-priority vehicles are not permitted to use the priority lanes so both CRITIC and CRITIC+ are disabled. In CRITIC, all non-prioritized vehicles moving on a congested non-priority lane are allowed to use the under-utilized priority lane if no bus is detected on it. Finally, in CRITIC+, only selected non-prioritized vehicles based on the promotion probability computed in Equation 6 are allowed to move to a priority lane if it is under-utilized.

Figure 2 depicts the achieved Average Travel Time (ATT) for different vehicle classes under varying percentages of buses inserted in the traffic flow. We can see that both CRITIC and CRITIC+ lead to a lower ATT compared to the baseline with the most important reduction achieved when the percentage of buses is 12%. We notice as well that CRITIC+ has lower ATT than CRITIC in many cases. This shows the advantage of selecting a subset of vehicles to use the priority lane, instead of allowing all vehicles, as the latter might sometimes just shift the congestion to the priority lane instead of using it to virtually increase the road capacity and relieve the congestion situation. Moreover, a large number of lane change maneuvers leads to additional delays due to the coordination needed between connected vehicles for increased safety [10]. These results highlight that not only electric and private vehicles benefit from CRITIC and CRITIC+ but also the buses, which are the prioritized vehicles that use the priority lane reserved for them. The reason behind that is the fact that buses will not use priority lanes during their whole trip but only when they exist on a road segment, in this case, 25% of road segments have a priority lane, and as CRITIC and CRITIC+ alleviate the congestion on non-priority lanes this will benefit the buses as well when they use them.

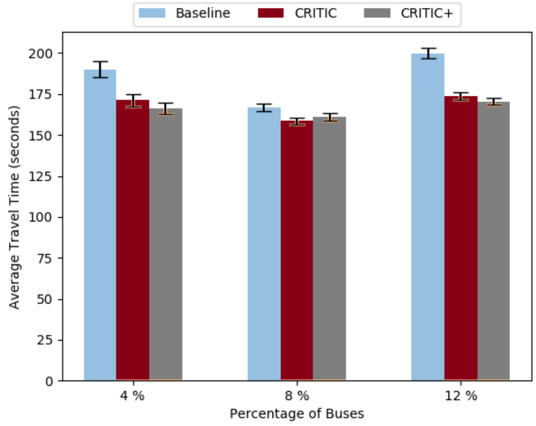
Figure 3 highlights the relation between the percentage of available bus lanes in the road network and the efficiency of CRITIC and CRITIC+ in reducing the ATT. Similar to the previous results, CRITIC+ outperforms CRITIC in most of the cases. Moreover, the benefit of both CRITIC and CRITIC+ is more important when the percentage of bus lanes is higher (i.e., 50%) because in this latter case traffic congestion is worse since the capacity of non-priority lanes is lower compared to the scenario of 25% of bus lanes. From this, we conclude that our proposed CR-TMS performs better when the percentage of bus lanes (or reserved lanes in general) in the road network is higher.

V. Conclusion

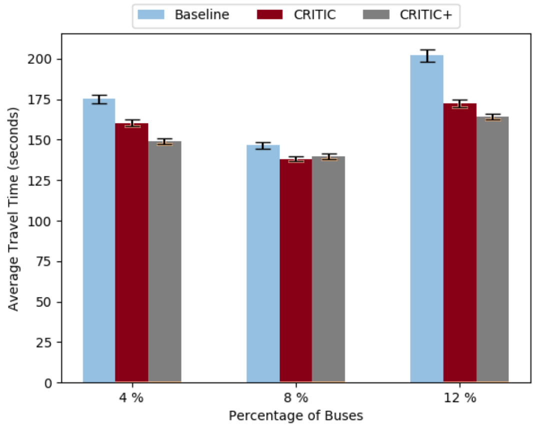
In this paper, we have tackled the problem of optimizing roads' traffic within the context of smart cities. We propose a strategy, inspired from cognitive wireless networks, to improve urban road lanes management. More specifically, our original idea in this work consists in improving the use of non-priority lanes by partially off-loading traffic onto priority lanes, without impacting the flow of traffic on the latter. The developed policy has clearly reduced the effects of congestion by reducing travel times for non-prioritized vehicles. An unexpected benefit of such a strategy has been to improve travel time even for prioritized vehicles such as buses. As a future work, we plan to develop a probabilistic model and advanced control strategy to achieve optimal



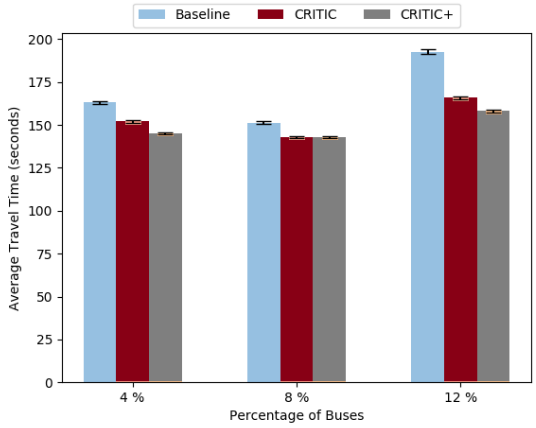
(a) All vehicles



(b) Buses



(c) Electric vehicles



(d) Private vehicles

Fig. 2: Impact of the percentage of buses on the achieved ATT in CRITIC and CRITIC+: a scenario of 7*7 grid map with 25% of bus lanes

performance of our solution and further improve traffic congestion mitigation efficiency.

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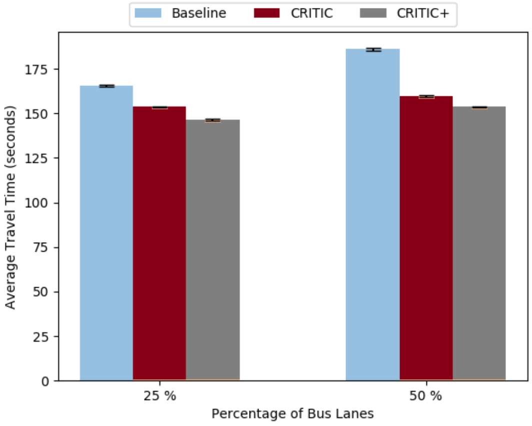
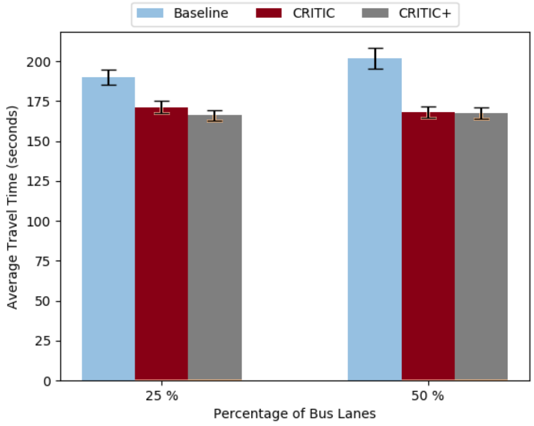
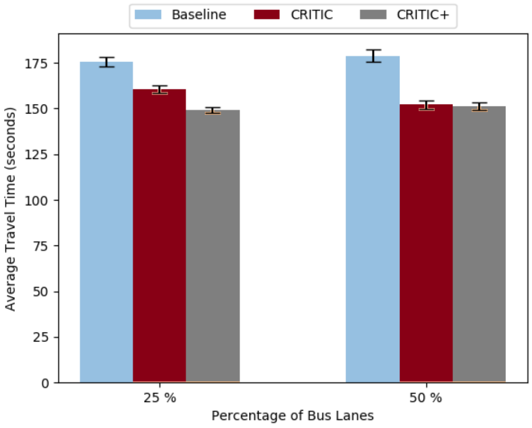


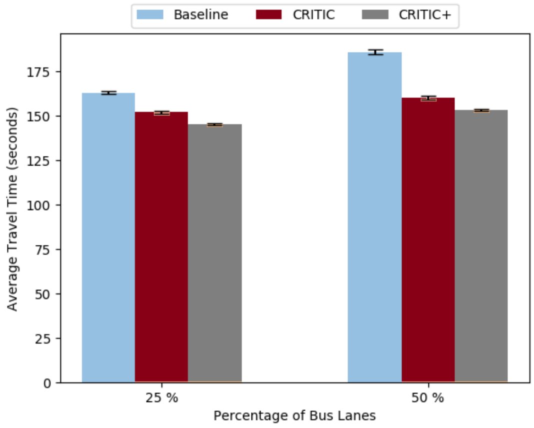
(a) All vehicles



(b) Buses



(c) Electric vehicles



(d) Private vehicles

Fig. 3: Impact of the percentage of available bus lanes on the efficiency of CRITIC and CRITIC+: a scenario of 7*7 grid map with 4% of buses in the traffic

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